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STRING THEORY:
LESSONS FOR LOW ENERGY PHYSICS?

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Abstract

This talk considers possible lessons of string theory for low energy physics. These are of two types. First, assuming that string theory is the correct underlying theory of all interactions, we ask whether there are any generic predictions the theory makes, and we compare the predictions of string theory with those of conventional grand unified theories. Second, string theory offers some possible answers to a number of troubling naturalness questions. These include problems of discrete and continuous symmetries in general, and CP and the strong CP problem in particular.

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I have been asked by the organizers to discuss lessons that string theory might hold for low energy physics. This is a difficult charge. Some would argue that it is likely that string theory is the underlying theory of all interactions. In this view, we should simply wait until we understand how to connect the theory to reality. Others argue that the theory might well have nothing to do with nature, or – perhaps worse – that while it may be the "theory of everything" it might take millennia to connect it to reality. Most who hold these views believe that the theory is unlikely to teach us anything. In this lecture, I would like to adopt a middle ground. My own opinion is that string theory, whether or not it is ultimately correct, has a number of interesting lessons to offer us. After all, it is, at least potentially, a truly unified theory, and thus it is possible to ask of it many of the questions which trouble us in field theory. As we will see, string theory has already provided interesting answers to several problems of symmetries and naturalness; these will be the subject of this talk. Numerous other important topics will not be covered here. For example, at the present time, much of the effort in string theory is being devoted to questions such as the possibility of information loss in black holes. While these studies are very exciting, they have not yet yielded definite conclusions.

In thinking about problems which trouble us in conventional field theory model building, I believe it is reasonable to assume that anything which happens in string theory can occur in whatever may be the ultimate theory. In this spirit, I will attempt to apply the general lessons string theory teaches about naturalness to more conventional problems of low energy supersymmetry and grand unification. However, apart from general observations about how this prototype unified theory resolves (or fails to resolve) certain questions of naturalness, we should also keep in mind the possibility that string theory *is* the ultimate theory of nature. So it is also interesting to ask whether string theory itself makes any generic predictions, independent of the details of compactification and the like. Unfortunately, to date the answer is no, but there are some features which are *almost* generic. I will mention some of these as I go along. Of course, my choices here, as those above, reflect my prejudices and interests. There are many things which will not be covered in any detail in this talk. In particular, I will only briefly mention some of the work which has gone into developing a theory of supersymmetry-breaking in string theory.[1] I will not have time to discuss efforts to develop a detailed phenomenology based on particular string models. Some of these will be presented by other speakers at this meeting. The reader should thus be forewarned.

All of the discussion will be in one particular framework: we will study classical solutions of the string equations [(super-conformal field theories] with four flat, Minkowski directions. Within this framework, string theory has scored a number of impressive successes, and it is worth listing them.[2] One finds:

1. Chiral fermions (generations)
2. Low energy supersymmetry
3. Axions
4. Massless Higgs doublets unaccompanied by triplets (more generally, particles which are massless which are permitted to gain mass by all space-time symmetries)
5. A rich structure of discrete symmetries
6. Gravity!

Items 3 and 4 already represent significant violations of conventional field-theoretic notions of naturalness. Some time ago, Nathan Seiberg and I suggested that the term "string miracle" should have a technical meaning, referring precisely to phenomena of this kind.[3] We will explain shortly in what sense the string axion is miraculous, according to this definition. Masslessness of Higgs doublets, in conventional grand unified theories – even with supersymmetry – requires fine tuning.⋆

String vacua have other remarkable features. Not only do they exhibit generations, for example, but in any given vacuum one can calculate (sometimes easily, sometimes with substantial labor) Yukawa couplings. So string theory does truly have pretensions to be a complete unified theory.

Unfortunately, against these successes one must weigh some serious – perhaps catastrophic – failures. I will list three here; some other potential problems will be considered later. By far the most serious problem is the cosmological constant problem; string theory has offered no insight into the question of why the cosmological constant vanishes. Specifically, whenever supersymmetry is broken and one can calculate the cosmological constant, it is non-zero and its magnitude agrees with naive estimates (*i.e.*, it is some power of the SUSY breaking scale times a suitable power of a cutoff).[4]

Closely related to this question is the problem that, while string vacua have many attractive features, there are far, far too many of them. There are two senses in which this number is large: there are many discrete choices of solutions (characterized, *e.g.*, by the dimensionality of space-time, the number of generations, and similar quantities), and there are continuous parameters. Among the latter are the value of the coupling constant, and the size and shape of the internal spaces. All of these are determined by the expectation values of dynamical fields; at least in perturbation theory these fields have no potential (in the case that supersymmetry is unbroken) and determining their values is part of the problem of supersymmetry breaking. Even without knowledge of the mechanism of supersymmetry breaking,

⋆ To the best of my knowledge, various proposals which have been offered to explain massless Higgs doublets in field theory fail once one considers higher dimension operators.

however, one can already see that we are headed for trouble:[5] necessarily, the potential for the field which determines the coupling – the "dilaton" – vanishes at zero coupling, so the potential will always have a minimum where the theory is free. Any other minimum is likely to lie at strong coupling, where perturbation theory is not useful. There have been some interesting proposals for solving this problem.[1] In addition, a great deal of machinery has been developed for dealing with the problem of supersymmetry breaking.[6] But it is probably fair to say that to date no compelling picture for supersymmetry breaking has been offered.

As we proceed, we will see that there are other problems. Perhaps these are somehow overcome; perhaps not. But even if string theory is not the ultimate theory of nature, it does provide an interesting framework – at the moment possibly the only framework – to address questions at a variety of scales which trouble particle physicists. The remainder of this talk, as suggested by our remarks above, has three themes:

1. We will ask whether there are any generic string predictions. While we cannot give a definitive answer, we will point out a number of features common to many string compactifications, which might have implications for low energy phenomenology.
2. We will consider the distinctions between string theory and more general field theories.
3. We will consider a number of questions of naturalness which have been raised in field theory model building, and see how they are resolved in string theory. Viewing string theory as a paradigm for unification, we will suggest that phenomena which occur in string theory might plausibly occur in any ultimate theory, and thus these observations can (and will) serve as a guide to model building.

In the next section, we will compare string theory with conventional grand unified theories. We will also note that string theory seems unlikely to yield something like the minimal supersymmetric standard model: there are likely to be gauge singlets and R-parity is likely broken. We will point out that string theory provides no magic answers to the problems of flavor-changing processes in these theories. In the third section we will discuss symmetries. We will see that string theory often produces approximate, global discrete symmetries. In the fourth section, we will consider CP and the strong CP problem. We note that CP is a gauge symmetry in string theory, which must be spontaneously broken. This breaking may occur near M_p, or at lower energies. In the former case, axions are probably required to solve the strong CP problem, and we consider some aspects of axions in string theory. In the case of lower energy breaking, it is natural to consider other possible solutions. Within the framework of low energy supersymmetry, this leads to general predictions about the form of CP violation at low energies.

To begin, it is worthwhile to make some comparisons between string theory and conventional grand unified theories. One of the striking features of string theory is that the gauge couplings are all equal at the fundamental scale of the theory[7] (which we can loosely think of as the string scale of the Planck mass). In other words, they are precisely equal at the tree level. From a field theory point of view, this is quite amazing. In a conventional grand unified theory, higher dimension operators can correct such relations (albeit by a small amount). For example, in SU(5), if Σ is a 24 with a non-zero vev, higher dimension operators such as $1/M_p^2 \mathrm{Tr}\Sigma^2 F^2$ will break the equality between the couplings. This illustrates that the effective field theory which describes strings, while it contains operators of arbitrarily high dimension (already at tree level), is a very special one. It is also true that under quite general circumstances, $\sin^2(\theta_W) = 3/8$, exactly, at tree level.[8]

While remarkable, these statements have an unfortunate consequence for string phenomenology. There has been much excitement recently over the fact that the minimal supersymmetric standard model (MSSM) leads naturally to unification of coupling constants with a unification scale of order 10^{16} GeV. In string theory, on the other hand, one can give good arguments that unification occurs very near M_p.[7] Thus string unification requires that one have something beyond the minimal standard model: additional particles and interactions, some early partial unification, or something else.[9] This is not a disaster, but it is disappointing that things do not work simply.

Returning to the comparison of strings and GUT's, there are some striking differences. First, GUT type relations among Yukawa couplings do not hold.[2] In addition, if one examines the transformation laws of the light fields under discrete symmetries, one finds, in general, that they are not related as they would be in a grand unified theory. Typically in a field theory the light fields would consist of complete multiplets of the unified gauge group [*e.g.*, the $\bar{5}$ and 10 of SU(5)], each transforming in the same representation of the discrete symmetry.⋆ There may also be incomplete mirror multiplets (*e.g.*, the Higgs doublets in a supersymmetric SU(5) theory); these will also be mirrors with respect to the discrete symmetry, *i.e.*, they will have quantum numbers which permit a mass term. In typical string models, on the other hand, the discrete quantum number assignments look almost

⋆ One can construct counterexamples to this statement in the following way. Suppose that the discrete symmetry which survives to low energies is a linear combination of the original discrete symmetry and a gauge transformation of the unified theory. Then different elements of a multiplet will transform differently. This might give a framework in which to explain the existence of massless doublets, though I have not succeeded in doing this.

random (consider the models discussed in ref. 2, adding Wilson lines). They seem subject only to very mild constraints.[10]

Both of these observations suggest strategies for model building, which have already been exploited in various string-inspired models. It is worth mentioning some other features of string compactifications with implications for model building. One is that these models typically predict the existence of light gauge singlets. It is probably not reasonable to call this a string prediction; I know of no theorem that these fields need arise. However, they are extremely common, and this suggests one should seriously consider extensions of the minimal theory with such fields.[†] Such theories suffer from well-known problems[11], such as appearance of large tadpoles, but these can readily be solved with discrete symmetries.

A second point concerns R-parity violation. The discrete symmetries which tend to arise at low energies are often rather intricate. If string theory, or something like it, is the underlying theory, there is no reason to think that the symmetry which forbids proton decay is the simplest R-parity. This suggests one should take very seriously the possibility of R-parity violation.[12]

Since we are on the subject of low energy supersymmetry, there is another lesson which string theory teaches. It is well known that absence of flavor changing neutral currents in supersymmetry requires an approximate degeneracy of squark masses. Such a degeneracy is not enforced by any symmetry. In hidden sector supergravity models, for example, if Z is a hidden sector field, and ϕ_i are observable fields, terms in the Kahler potential of the form

$$\gamma_{ij} Z^\dagger Z \phi^{i\,\dagger} \phi^j \tag{1}$$

contribute to scalar masses. Mass degeneracy requires that γ should be proportional to the unit matrix. In a generic string vacuum, there is no reason to expect such a feature. Kaplunovsky[13] has calculated many of these couplings and shown, indeed, that nothing of this sort happens.

That there is no generic solution does not mean that there do not exist solutions. In the context of string inspired models, there has been one interesting suggestion: perhaps at the large scale, the scalar masses are essentially zero, while gaugino masses are not.[14] In ref. 15, it is shown that with some reasonable naturalness constraints, one can obtain in this way a low energy spectrum with adequate degeneracy.[‡] Alternatively, the problem can be solved if supersymmetry breaking is

† Note here that I am not referring to the moduli of $(2,2)$ compactifications, but rather, for example, to the O(10) singlets which arise in E_6 and which can couple to Higgs doublets.

‡ Apart from the imaginary part of the K-$\bar{K}$ mass matrix. This requires that some phases be small, as do the neutron and electron electric dipole moments. We will say more about CP later.

communicated from the hidden sector primarily by gauge interactions rather than by gravity.[16]

SYMMETRIES

In the context of model building in field theory, it has long been argued that global symmetries are unnatural. Apart from aesthetic considerations, it is not clear how such symmetries could survive gravitational corrections. String theory lends support to this view: one can prove, without much difficulty and with very weak assumptions, that there are no (unbroken) global continuous symmetries in string theory; all continuous symmetries are gauge symmetries.[17]

We have already remarked that discrete symmetries often arise in string theory. Frequently, one can think of these as gauge symmetries, or as general coordinate transformations in some higher dimensional space. In other words, they are surviving subgroups of some larger (continuous) gauge symmetry group. Indeed, it is widely believed that *all* discrete symmetries in string theory are of this kind, but this statement is difficult to prove. It is amusing that one *can* show that the Z_2 symmetry which exchanges the two E_8's of the heterotic string theory is a gauge symmetry.[18]

Independently of string theory, it has been argued that global discrete symmetries are likely to be broken by gravity.[19] On the other hand, gauged discrete symmetries of the type discussed above almost surely survive.[20] These considerations led Ibanez and Ross[21] to ask what consistency conditions might be required of a low energy theory in order that a discrete symmetry could be gauged. To address this question, they embedded the symmetry in a continuous group, and examined the anomaly cancellation conditions for this larger group. To derive conditions in this way requires making some assumptions about charges of heavy fields. In ref. 10, T. Banks and I pointed out that many string compactifications violate the simplest set of assumptions. The only constraints which hold independent of such assumptions can be understood in terms of instantons of the low energy theory.

In the course of this work, however, we made another discovery. In numerous ground states of string theory, one finds discrete symmetries with anomalies. One might try to conclude from this that either the corresponding symmetries are not truly gauge symmetries, or that the corresponding compactifications are inconsistent. However, in all of the cases which have been examined to date, it is possible to cancel the anomaly by assigning to the so-called model-independent axion a non-linear transformation law under the discrete symmetry. In other words, an instanton generates a non-zero amplitude of the type

$$\psi\psi\psi\dots\psi e^{-8\pi^2/g^2}e^{ia/f_A} \tag{2}$$

where a is the axion, and ψ denotes some space-time fermion field. If one ignores the instanton, the combination of fermions here (by assumption) violates the discrete symmetry, say by $e^{i\Delta}$. However, by assuming $a \rightarrow a - \Delta$ under the symmetry, the amplitude becomes invariant. Of course, this means that the non-anomalous discrete symmetry is spontaneously broken. What is much more interesting, however, is that in perturbation theory there is nothing wrong with the original (unbroken) symmetry. Only non-perturbatively is there any violation of the symmetry. This suggests that it is reasonable to consider global discrete symmetries, which are only broken by small amounts. Such a possibility is of interest for questions such as fermion mass hierarchies and flavor changing neutral currents, as well as for suppressing baryon violation and other unwanted processes in supersymmetric models.

CP, STRONG CP, AND ALL THAT

In field theory, the axion solution of the strong CP problem begins by postulating that classically and in perturbation theory, nature possesses a Peccei-Quinn symmetry,

$$a(x) \rightarrow a(x) + \delta \ . \tag{3}$$

This symmetry is then broken non-perturbatively by QCD effects. From a field-theoretic perspective this may be "natural" in the sense that, given the symmetry, the corrections are small; still, it is disturbing to postulate such a broken symmetry.[22] As has been stressed recently, however, if gravity violates global symmetries, it is almost impossible to understand how the axion solution can possibly work.[23] Suppose that the Peccei-Quinn symmetry is broken by a high-dimension coupling,

$$\mathcal{L}_{SB} = \frac{\gamma}{M_p^n} \mathcal{O}_{n+4} \tag{4}$$

where $\mathcal{O}_{n+4}$ denotes an operator of dimension $n+4$, and γ is a numerical constant, presumably of order one. Such a coupling will generate a linear term in the axion potential, with coefficient of order

$$\frac{\gamma f_a^{n+3}}{M_p^n} a(x) \ . \tag{5}$$

If $f_a \sim 10^{11}$ GeV, then requiring $\theta < 10^{-9}$ means that one must have $n \geq 8$, *i.e.*, one must suppress all potential symmetry breaking operators up to dimension 12. If $f_a = M_p$, one needs to suppress all possible symmetry-breaking operators.

From this perspective, it should be clear why I referred to the presence of axions in string theory as a "miracle." In compactifications of the heterotic string, there is always at least one, "model-independent" axion. The existence of this axion can be understood in at least two ways. First, the low energy theory always contains a two-index antisymmetric tensor field. This field is equivalent to a scalar. The couplings of the antisymmetric tensor are governed by a gauge principle; this principle can be shown to forbid a mass term for the scalar. Alternatively, if one studies the vertex operator for this axion, it is readily seen to be (from a world-sheet viewpoint) a total divergence at zero momentum, indicating that the axion has only derivative couplings. It is also not hard to show that this field has the correct $F\tilde{F}$ couplings.

While the presence of this axion is "miraculous," there are two reasons why it might not solve the strong CP problem. First, in many string models, there are strong gauge groups besides SU(3). Thus one may need additional axions. Second, the large decay constant means that it violates the cosmological limit, $f_a < 10^{12}$ GeV.[24] It is not clear how much one should trust this limit; various loopholes have been suggested through the years.[25]

However, for now, let us take the limit seriously, and ask how one might obtain such an axion. In the past, a number of authors have considered the possibility that the Peccei-Quinn symmetry might arise accidentally, as a consequence of properties of the low dimension operators in some effective field theory. In the context of string theory, at least two sets of authors have suggested that discrete symmetries might lead to such an approximate symmetry.[26,27] The authors of ref. 27 attempted to estimate the effective θ which would appear in their model, precisely along the lines discussed above. One extremely nice feature of the string-inspired models considered by these authors is that the axion decay constant is automatically of order[28] $M_{INT} \sim \sqrt{M_W M_p} \sim 10^{10}$–$10^{12}$ GeV, *i.e.*, within the allowed axion window. The scale of the vev's which break the PQ symmetry is indeed typically of this order. Various aspects of these ideas, including certain pitfalls not noted in earlier work, are discussed in ref. 29.

Even if string theory produces an axion in this way, there is another concern: the axion may fix θ to a CP-violating value. It is not necessarily true that an axion in string theory (or field theory) solves the strong CP problem. There is no guarantee, in general, that effects in the high energy theory don't give rise to contributions to the axion potential which are larger than the QCD contributions, particularly in theories in which the QCD β-function is small or positive at high energies.[30] In such cases, if the high energy theory is not CP-conserving, there is no reason for the minimum of the axion potential to lie at the CP-conserving point, so the Peccei-Quinn solution can be spoiled. In ref. 30, it was shown that small instantons can lead to precisely this effect, and that this might occur in many string compactifications. Perhaps even more worrisome is the observation of Shenker that there may be effects in string theory which behave as $e^{-1/g}$, *i.e.*, which are far larger than non-perturbative effects in the low energy field theory.[31] If present, these could easily dwarf the QCD contribution to the axion potential.[⋆] All of this suggests that one should consider theories where CP is unbroken at M_p, and spontaneously broken by other fields at much lower energy.

In conventional model building, an alternative to the axion idea has been considered from time to time. This is the possibility that CP is an exact symmetry of the underlying lagrangian, and that the "bare" θ consequently vanishes. This, by itself, is not enough to insure that the observed $\theta_{\rm QCD}$ is small enough. Nelson[32] has proposed a scenario for obtaining sufficiently small θ; this scheme has been further developed by Barr.[33]

Remarkably, one can show that in string theory, what we refer to in four dimensions as CP is a gauge symmetry![34,18] It is a combination of a general coordinate transformation in the ten-dimensional space and a gauge transformation in O(32) or $E_8 \times E_8$. One consequence of this observation is that string theory cannot possess bare θ-parameters; $\theta_{\rm QCD}$ is "calculable" in this sense. CP *can* be spontaneously broken in two ways:

a. As Strominger and Witten noted some time ago,[35] string compactifications typically contain CP odd "moduli" (fields with no potential; one can think of their expectation values as determining the size and shapes of the internal spaces in these theories). Expectation values for these fields break CP. Such vev's correspond to breaking of CP near M_p. It is hard to see how $\theta_{\rm QCD}$ could turn out to be small under these circumstances, unless there are axions. One will still have to worry about the problems described above.

b. CP can be broken by expectation values for CP-odd matter fields. Apart from other virtues which we will describe below, this has the feature that unknown high energy effects won't spoil the Peccei-Quinn solution.

Recently, we have been considering a scenario of the second type. We have constructed a number of "string-inspired models" in which a Nelson-Bar type mechanism is operative. Consider unification in the group E_6 (of the type suggested by the simplest Calabi-Yau compactifications).[2] Matter fields fall in 27's and $\overline{27}$'s of E_6. Under the usual SO(10) gauge group, the 27 decomposes as

$$27 = 16 + 10 + 1 \ . \tag{6}$$

Of particular interest two us are the two standard model singlets in this decompo-

⋆ This problem is connected to the observations of ref. 23, in the case of accidental axions with decay constant less than M_p. In that case, small instantons generate effective interactions which violate the would-be symmetry. This can only occur if the operators of interest violate the supposed discrete symmetry. This, in turn, means that the discrete symmetry is anomalous in the sense described above. The coefficients of the symmetry violating operators are exponentially small, in this case; the point here is that this may not be small enough.

sition. Apart from the O(10) singlet, which we will denote by S, the 16 contains a particle which can be identified as the right-handed neutrino, which we will denote $\mathcal{N}$. The 10 contains two colored fields with the quantum numbers of the $\bar{d}$ quark and its antiparticle; we denote these by $\bar{q}$ and q, respectively. If one assumes that the low energy theory contains soft supersymmetry breaking terms of the usual type, then it is natural, as above, to obtain vev's for some of the S and $\mathcal{N}$ fields of order 10^{10} GeV, where the S vev's are real while the $\mathcal{N}$ vev's are complex and CP violating. This gives rise to a mass matrix of the form discussed by Nelson and Barr:

$$\langle S \rangle \, q\bar{q} + \langle \mathcal{N} \rangle \, q\bar{d} \tag{7}$$

As these authors have pointed out, this leads to a quark mass matrix which is complex, but whose determinant is real. Judicious choice of discrete symmetries insures that other potential sources of θ are sufficiently suppressed. For example, they insure reality of the Higgs mass matrix. They can also assure other phenomenologically important properties, such as suppression of B and L violation.

Particular models of this type are described in ref. 36. They tend to be rather artificial-looking. However, they all make certain predictions: they predict that the only source of CP violation at low angles is the KM phase; there are no additional phases in gaugino mass matrices, etc., and θ is extremely small.

CONCLUSIONS

My own view, from these observations, is that we have learned some things from string theory, mostly about questions of naturalness. Among these:

1. While exact global continuous symmetries are unnatural, gauged discrete symmetries are quite common; moreover, it is reasonable to postulate weakly broken global discrete symmetries.
2. It is plausible that if nature is supersymmetric at low energies, it has a more complicated structure than that of the MSSM.
3. There is no obvious reason to think that, if nature is supersymmetric, there should be any approximate flavor symmetry of squark masses at the highest scales. It is still necessary to search for particular mechanisms which might explain the smallness of flavor changing neutral currents.
4. It is not unreasonable to postulate axions at very high scales; axions at lower scales may arise accidentally as consequences of discrete symmetries.
5. Spontaneous CP-violation with small θ can arise as a consequence of discrete symmetries. This may have other phenomenological consequences, such as vanishing of CP-violating soft supersymmetry breaking phases.

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